FINAL REPORT

DESIGN AND DEVELOPMENT OF A BLASTHOLE DEPTH MEASUREMENT TEST SET

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Work on this project was conducted under the auspices of the Department of Energy, Mines and Resources.

DAVIS File Number: 85-171
DSS File Number: 07SQ.23440-6-9068
DSS Contract Number: 23440-6-9068/01-SQ
DSS Scientific Authority: Dr. Jay Pathak

52 pp.

SEPTEMBER 1987

MICROMEDIA

5-171R.1/248

EXECUTIVE SUMMARY

The following report explains the theoretical and practical considerations in acoustically measuring blastholes and Muck Pile height in a Vertical Crater Retreat mining process. The report explains basic acoustic theory and proceeds to explain such factors as:

- Frequency,
- Power level requirement,
- Attenuation,
- Accuracy, etc.

The results of laboratory experiments and field trials are given, along with conclusions and recommendations.

RÉSUMÉ

Le rapport suivant explique les considérations théoriques et réalisables de mesurer acoustiquement les trous de mine et la hauteur de minerai dans une galerie verticale en développement d'une exploitation minière. Le rapport explique la théorie acoustique de base et continue pour expliquer des facteurs tels que:

- la fréquence,
- le niveau de puissance nécessaire,
- l'atténuation de précision ect.

Les résultats des expériences en laboratoire et d'essais en campagne sont fournis ainsi que les conclusions et recommendations.

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1.0 INTRODUCTION

In underground hardrock mining methods such as vertical retreat stoping (see Figure 1), it is essential that the depth of each blasthole and the height of the muck pile are known. This information is required in order to estimate the volume and weight of blasted muck, to plan the next blast and for drawpoint mucking control. The current method of measuring blastholes and the muck pile height is to lower a rope or tape down the hole. This technique is accurate but quite time-consuming, so the design and development of an electronic measurement device was initiated.

This report is to explain the findings to date on the techniques proposed by DAVIS to:

1) Measure the depth of a blasthole in an underground hardrock mine,

2) Measure the height of the muck pile beneath the blasthole.

Included is a development of the theory, anticipated results, and experimental results. The technique investigated for blasthole measurement was acoustical resonance and Time Domain Reflection (TDR) was investigated for muck pile height measurement.

DAVIS briefly considered optical and radar ranging but felt that the bottom of the blasthole wouldn't present enough of a discontinuity for detection. There is also some doubt as to whether the blastholes will be straight enough to allow a "line of sight". Without a line of sight the path length of such a signal would be somewhat longer than the blasthole, because of multiple reflections, and determining the blasthole length would be extremely difficult. For these reasons, DAVIS chose to use acoustics.

The wavelengths of acoustic waves can be made long enough that diffraction will allow bending to follow curved holes. Furthermore, the bottom of a blasthole represents a substantial discontinuity with respect to acoustic waves.

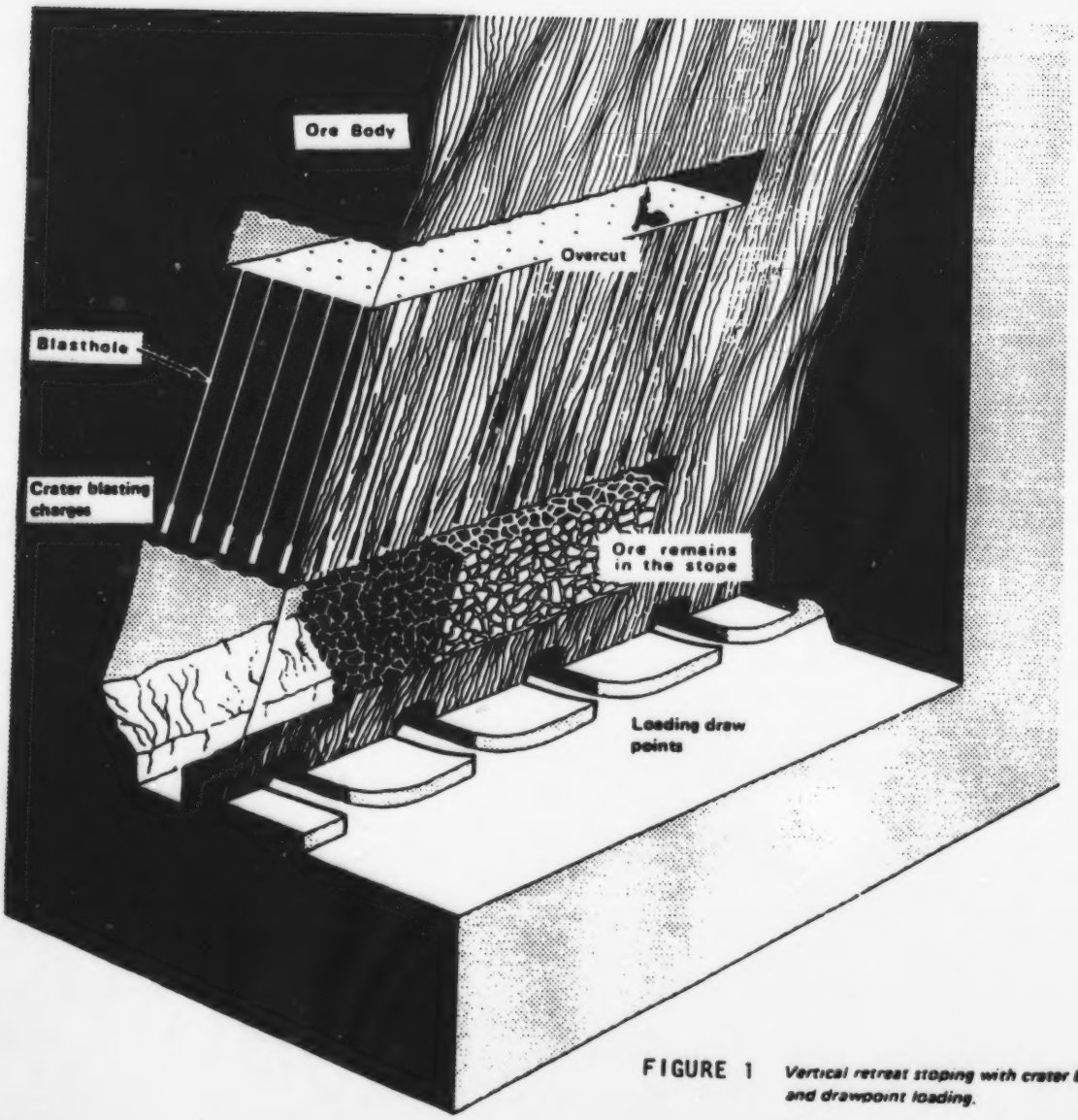

FIGURE 1 *Vertical retreat stoping with crater blasting and drawpoint loading.*

2.0 THE NATURE OF SOUND

It is desirable at this point to give a brief description of sound in air, since it is the underlying phenomena used to make measurements.

When a source of sound (such as a loudspeaker) vibrates, it imparts to the air pulses of momentum. These pulses travel through the air at the speed of sound, c. The air which holds a momentum pulse at a given instant represents a localized high pressure region known as a compression. The lower pressure region between two pulses is known as a rarefaction. If the source of sound is vibrating with a frequency of f Hertz, it will generate f compressions per second. The distance between successive compressions is the wavelength λ, and the relationship between λ, f and c is given by:

$$c = f\lambda$$

Although the compressions move through the air at the speed of sound, the air particles have no average motion and merely oscillate with simple harmonic motion about their mean positions. Figure 2 shows the relationship between (a) particle distribution, (b) particle displacement and (c) particle velocity.

For the purposes of measuring blastholes acoustically it is useful to introduce another expression, specific acoustic impedance.

$$z = \text{specific acoustic impedence} = \frac{\text{excess pressure}}{\text{particle velocity}} = \frac{p}{\dot{n}}$$

This term is the ratio of force per unit area to a velocity and gives a measure of the impedance of the medium to the sound waves. When sound waves meet a boundary separating two media of different acoustic impedance, some of the sound is reflected and some is transmitted. This phenomena is the basis for the proposed measuring system.

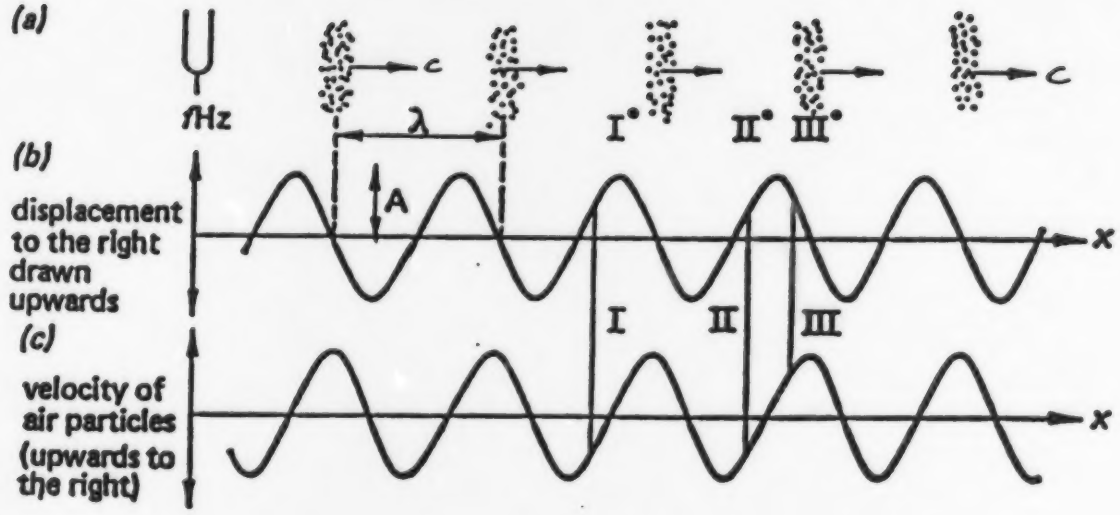

FIGURE 2 - A SOUND WAVE

2.1 PRINCIPLES OF ACOUSTIC RESONANCE

If a source of sound (such as a loudspeaker) is placed over the top of the blasthole, the sound will propagate down the hole. The boundary formed by the bottom of the blasthole and the top of the stope represents an acoustic impedance mismatch and consequently some of the sound waves will be reflected back up to the top of the blasthole. The incident and reflected waves interact to form a standing wave. The phase relationship of these two waves is a function of the length of the column of air, the speed of sound and the frequency of the sound wave. At certain frequencies the waves are in phase and a condition known as resonance occurs. Phase and frequency relationships can be determined electronically and thus provide a means for determining the length of the hole.

If a sound wave encounters a second medium of higher specific acoustic impedance the reflected pressure will be in phase with the incident wave. On the other hand, if the second medium is of lower specific acoustic impedance the reflection will be out of phase. In practical terms this means that the bottom of a blasthole is of lower impedance if it is open, and of higher impedance if it is blocked. Another way of looking at this is to view the situation as a boundary value problem where an open end represents a place of zero pressure change during the oscillation and a place of maximum air movement. A closed end represents a place of zero movement and maximum pressure variation. Maximum amplitude of oscillation will occur when the frequency of the sound used to excite the air column is the same as one of the natural frequencies of the column. These resonant frequencies, for a column of length L, occur as follows:

For an air column closed at one end

$$f = \frac{c\,(2n + 1)}{4L} \qquad n = 0, 1, 2, 3...$$

For an air column open at both ends
or closed at both ends

$$f_n = \frac{cn}{2L} \qquad n = 1, 2, 3 ...$$

The first three harmonics of a column closed at one end are illustrated in Figure 3. It should be noted that if a speaker is tightly coupled to the air column, it will behave as a closed end and if it is loosely coupled, it will behave as an open end. The test apparatus currently being used is tightly coupled so that the harmonics of an ordinary blasthole will be that of a column closed at one end.

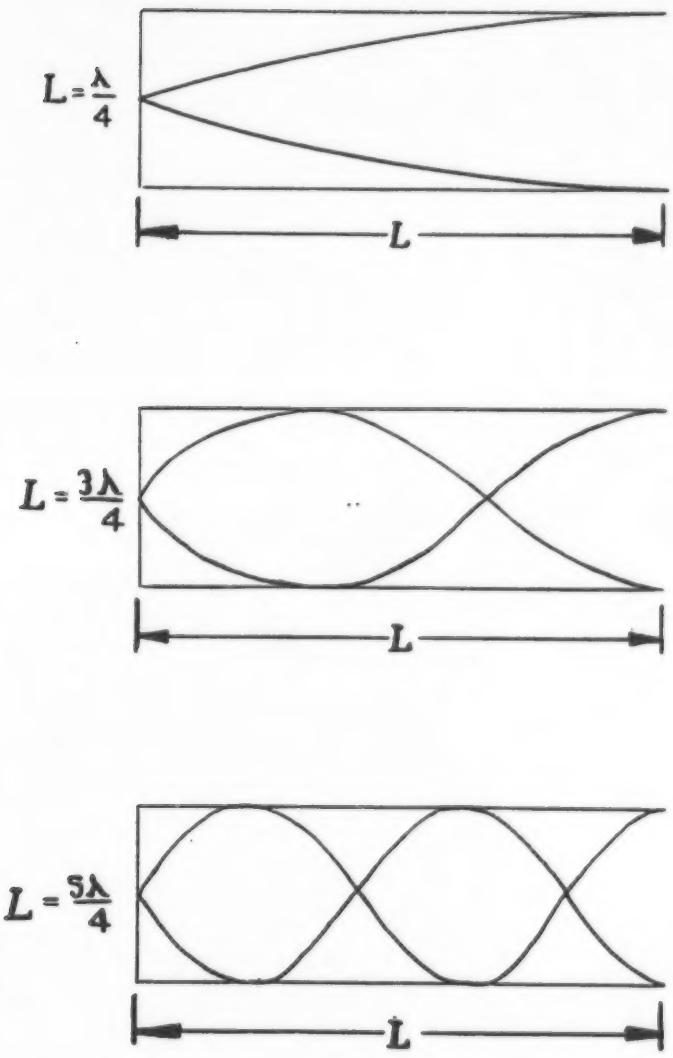

FIGURE 3 FIRST THREE HARMONIC MODES OF AN AIR COLUMN

3.0 BLASTHOLE MEASUREMENT USING RESONANCE

If a sound source is placed over the blasthole and a microphone is placed in the hole, resonance can be achieved by varying the frequency of the source until the microphone signal peaks. Determining the length of the hole, L, based on this resonant frequency would require several assumptions. First, based on an assumption that the blasthole is open at the bottom and free from any obstructions, the appropriate equation for resonant frequencies can be selected. Once this is done an assumption for the value of n (i.e. which harmonic is being excited) would have to be made based on such things as previous knowledge of hole length and the accuracy to which c and f are known. These assumptions are quite clearly not desirable or even feasible so DAVIS developed a technique to eliminate them.

As explained earlier, an open hole will resonate at these frequencies,

$$f_n = \frac{c\ (2n + 1)}{4L} \qquad n = 0, 1, 2, 3 \ldots$$

and closed hole resonant frequencies are given by:

$$f_n = \frac{cn}{2L} \qquad n = 1, 2, 3 \ldots$$

Now, if two successive harmonics are excited, it can be shown that both the length and end-of-hole condition can be determined. In the case of the open hole

$$f_{n+1} - f_n = \Delta f = \frac{c}{4L} \quad [2(n+1) + 1 - (2n + 1)]$$

$$\Delta f = \frac{c}{2L}$$

$$\therefore \quad L = \frac{c}{2\Delta f}$$

For a closed hole

$$f_{n+1} - f_n = \Delta f = \frac{c}{2L} \quad [n + 1 - n]$$

$$\Delta f = \frac{c}{2L}$$

$$\therefore \quad L = \frac{c}{2\Delta f}$$

It is now apparent that Δf is the same for a blasthole regardless of its end condition and therefore L can be determined. Δf can also be used in conjunction with f_n to determine the end condition. For a closed hole

$$\frac{f_n}{\Delta f} = \frac{cn}{2L} \cdot \frac{2L}{c} = n, \text{ an integer}$$

For an open hole

$$\frac{f_n}{\Delta f} = \frac{c\ (2n + 1)}{4L} \cdot \frac{2L}{c} = n + 1/2, \text{ a non-integer}$$

3.1 ACCURACY CONSIDERATIONS

As specified by EMR, it is desirable to measure the blastholes to ±.5% accuracy. The accuracy of the measurement is dependant on two critical parameters, the accuracy to which the resonant frequencies can be measured and the accuracy to which the local speed of sound is known.

3.1.1 Frequency Measurement

There are several factors which govern the frequency range selected. To begin with, the frequency should be significantly less than the cutoff frequency of the tube. As the wavelength is reduced to the point where it is equal to twice the tube diameter, the wave becomes increasingly non-planar. This increases attenuation and also makes resonance detection difficult. Therefore, any frequency used should be less than the cutoff frequency.

$$f << f_{CUTOFF} \qquad f_{CUTOFF} = \frac{c}{2d}$$

In general, error in hole measurement will decrease as the frequency decreases but this will be limited by the capabilities of the speaker, microphone and circuits.

As an example, suppose the harmonic frequencies can be measured to .1% accuracy. The speaker, microphone and circuits are very linear at frequencies of 100Hz and up. For a 20m blasthole, Δf is given as follows:

$$\Delta f = \frac{c}{2L} \qquad c = 343.3\ \frac{m}{s} \text{ @ } t = 20°C$$

$$\Delta f = \frac{343.3}{2(20)} = 8.58 \text{ Hz}$$

If a frequency sweep starts at 100Hz and increases, the first resonance will occur at 107.25Hz (corresponding to n=12). The next harmonic will be at 115.83Hz (corresponding to n=13). With these two harmonics the length L is calculated as follows:

$$L = \frac{c}{2\Delta f}$$

$$= \frac{343.3}{2[(115.83 \pm .1\%) - (107.25 \pm .1\%)]}$$

$$= \frac{171.65}{(115.83 \pm .12) - (107.25 \pm .11)}$$

$$= \frac{171.65}{8.58 \pm .23}$$

$$= \frac{171.65}{8.58 \pm 2.68\%}$$

$$= 20m \pm 2.68\%$$

Now, if the sweep had started at 50Hz, the harmonics encountered would be 51.48Hz and 60.06Hz. The calculation of L would be as follows:

$$L = \frac{c}{2\Delta f}$$

$$= \frac{343.3}{2[(60.06 \pm .1\%) - (51.48 \pm .1\%)]}$$

$$= \frac{171.65}{(60.06 \pm .06) - (51.48 \pm .05)}$$

$$= \frac{171.65}{8.58 \pm .11}$$

$$= \frac{171.65}{8.58 \pm 1.3\%}$$

$$= 20m \pm 1.3\%$$

These two examples show that for a given accuracy of harmonic frequency measurement (in these examples ±.1%) the accuracy of the measurement improves at the lower harmonics.

It is not just the stability of the oscillator, but also the ability to detect resonance that determine the harmonic frequency's accuracy. During the course of laboratory experiments, DAVIS has discovered two techniques which improve the measurement accuracy considerably. The first technique determines the resonant frequencies more accurately, the second technique improves the determination of the hole length during data reduction.

Experimental data is included in Appendix "A" and shows the results of using these two techniques. DAVIS is currently detecting resonance using an experimental set-up similar to that in Figure 4. The function generator produces a sinusoidal signal of variable frequency which is amplified and fed into a speaker. A microphone placed near the end of the pipe monitors the sound level and produces a signal which is amplified and then observed on an oscilloscope. To find a resonant frequency, the operator varies the frequency of the function generator until he observes an amplitude peak on the oscilloscope. The frequency at which this occurs can then be obtained from the frequency counter.

One problem with this technique is that small deviations from the resonant frequency result in only slight changes in amplitude and therefore the true resonant frequency may not be obtained precisely. DAVIS improved on this technique by averaging the upper and lower -3dB frequencies. With larger deviations from the resonant frequency amplitude drops off rapidly, and therefore small frequency changes near the -3dB points results in large amplitude changes (see Figure 5).

Assuming that the curve in Figure 5 is symmetrical about the resonant frequency, the resonant frequency can more accurately be determined by averaging two points on the steep parts of the curve. Generally, the curve is slightly asymmetrical and becomes more so at higher harmonics. As long as the two successive harmonics are on similarly shaped asymmetric curves, Δf won't be affected by asymmetry.

The second technique developed by DAVIS involved data reduction. Recall the example given earlier regarding measurement accuracy of a 20m hole at frequencies near 100Hz. With harmonic frequencies measured to .1% accuracy, the hole length could only be determined to

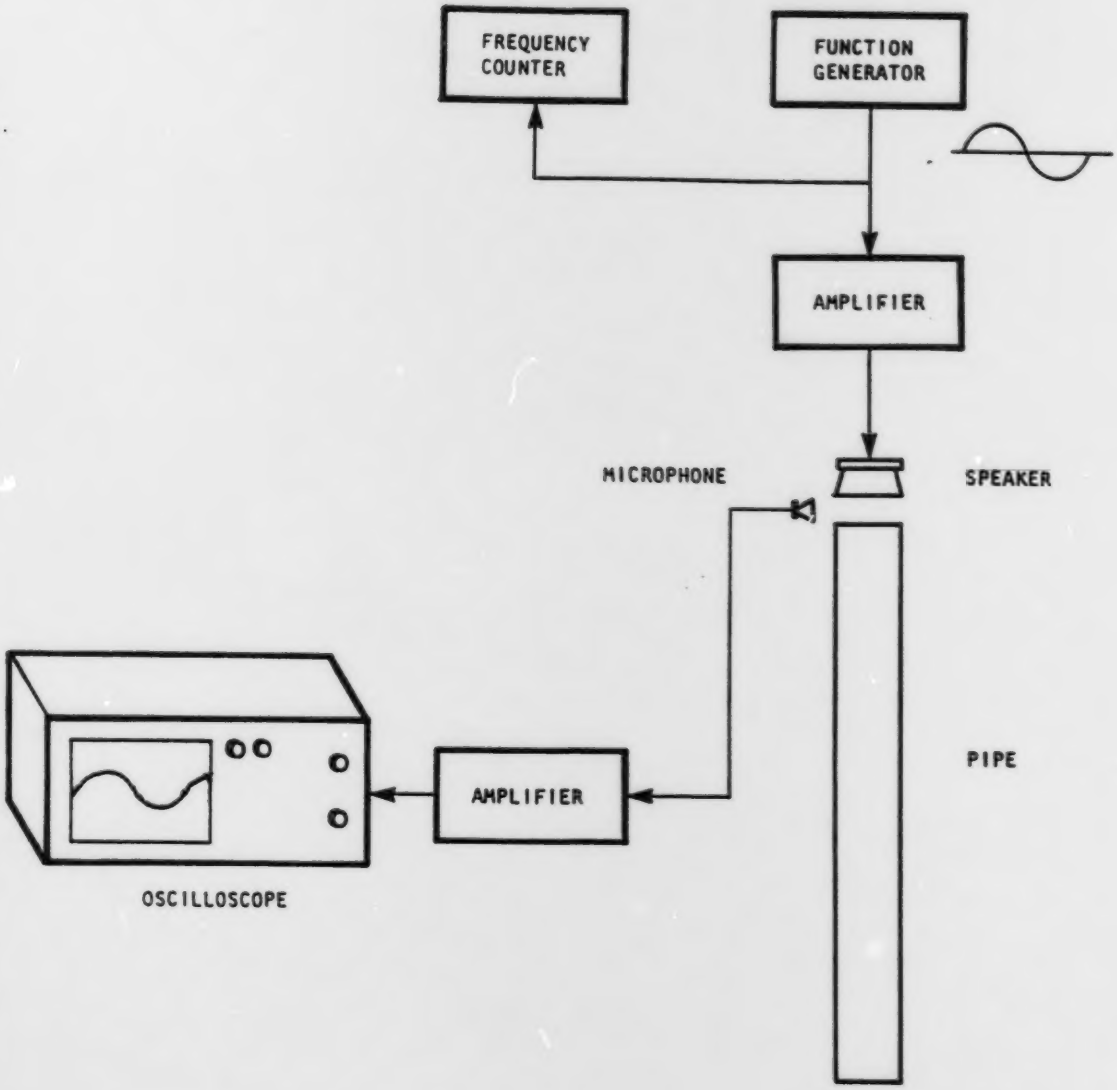

FIGURE 4 RESONANCE EXPERIMENT SET-UP

2.68% accuracy. This is the error in Δf, and assumes the speed of sound is known exactly. Recall:

$$L = \frac{c}{2\Delta f}$$

However, in determining end-conditions, it was also shown that an open hole yielded the following:

$$\frac{f_n}{\Delta f} = n+\tfrac{1}{2} \qquad \text{where n is an integer}$$

Once Δf is obtained, it may be divided into f_n. The resultant number will probably not be for the form $n+\frac{1}{2}$ because of the error in Δf, but if the error is small enough that n can be determined with certainty, then an iteration can be done that will significantly reduce the error in L. Going back to the example of the 20m hole recall that the harmonics were 107.25Hz and 115.83Hz with ±.1% error.

$$\frac{f_n \pm .1\%}{\Delta f \pm 2.68\%} = (n+\tfrac{1}{2}) \pm 2.78\%$$

Now, if 2.78% of $\frac{f_n}{\Delta f}$ is less than a $\frac{1}{2}$, n can be determined exactly. In this example, the error in n is small enough that n can be determined with certainty and for 107.25Hz, n = 12.

$$\Delta f = \frac{f_n}{n+\frac{1}{2}} = \frac{107.25 \pm .1\%}{12.5} = 8.58\text{Hz} \pm .1\%$$

This technique reduced the error in Δf (and L) by nearly 30 times.

3.1.2 Speed of Sound Measurement

There has been some concern about the effects of pressure, temperature, dust and humidity on measurement accuracy. The speed of sound in a gas is given by:

$$c = \sqrt{\gamma RT}$$

Where γ is the ratio of specific heats, R is the gas constant and T is the temperature in Kelvin. γ and R do vary slightly with large changes in temperature and pressure but for our purposes may be considered as true constants.

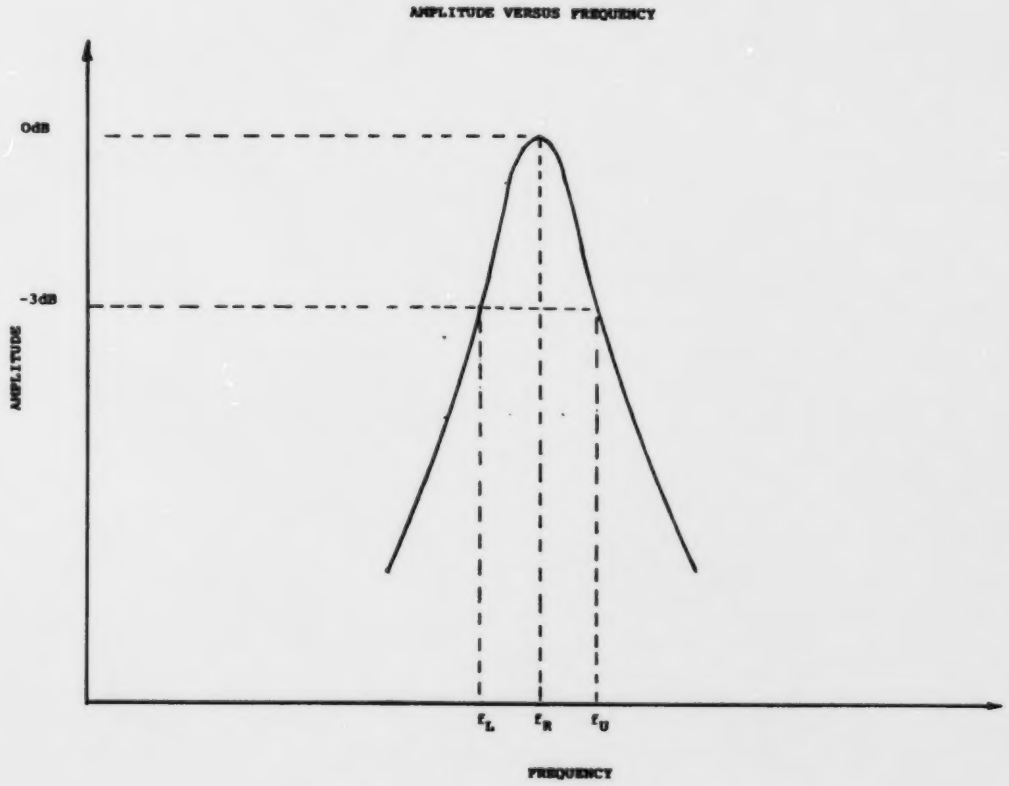

FIGURE 5 **AMPLITUDE - FREQUENCY CURVE FOR AN OSCILLATING AIR COLUMN**

Pressure

As seen by the equation above, pressure will not affect the speed of sound for our purposes.

Temperature

The speed of sound varies directly with $\sqrt{T}$. In the temperature range found in the mine (280 - 305K) the variance in the speed of sound is almost linear with respect to temperature.

$c = 20.05 \sqrt{T}$

$c = 335.5 \frac{m}{s}$ @ T = 280K

$c = 336.1 \frac{m}{s}$ @ T = 281K

There is approximately a .6 $\frac{m}{s}$ per Kelvin increase in c over the range of interest. This represents a .18% increase in c per degree Kelvin. Therefore, the temperature must be compensated for.

Dust

The speed of sound depends more on the elasticity of the gas than anything else. In a mining environment, the dust particles will be relatively incompressible and spaced far enough apart that the dust cannot act as a continuum. Under these circumstances, the dust will not affect the speed of sound.

Humidity

For a given gas, the speed of sound is given by

$c = \sqrt{\gamma RT}$

γ and R are different for different gases. Dry air is made up of several gases and a value of γ and R can be obtained for air by taking the γ and R values for the various gases and combining them with appropriate weighting factors. For dry air

$\gamma a = 1.400 \quad R_a = 287.074 \quad \frac{J}{Kg\ K}$

Now the problem of humidity can be addressed. Unlike the other gases in air, water vapour is present in varying amounts. The amount of water vapour in air can be determined by measuring the relative humidity and temperature and referring to a psychrometric chart. For steam at 300K and atmospheric pressure,

$$\gamma_s = 1.327 \qquad R_s = 461.52 \quad \frac{J}{Kg\ K}$$

In a mine, if the temperature can go as high as 25°C, the humidity ratio w can go as high as .02 Kg moisture per Kg dry air (this represents 100% relative humidity). The effective γ and R for air would then become

$$\gamma = \left(\frac{.02}{1.02}\right) \gamma_s + \left(\frac{1.0}{1.02}\right) \gamma_a$$

$$= .026 + 1.373$$

$$= 1.399$$

$$R = \left(\frac{.02}{1.02}\right) R_s + \left(\frac{1.0}{1.02}\right) R_a$$

$$= 9.049 + 281.445$$

$$= 290.494$$

The difference between $\sqrt{\gamma R}$ for dry air and 100% relative humidity at 25°C is

Dry air $\sqrt{\gamma R} = 20.05$

Moist air (100%R.H.) @ 25°C $\sqrt{\gamma R} = 20.156$

This change in γ and R would result in an increase in the speed of sound by approximately .5%. This figure represents a maximum, given by a relative humidity of 100% if the maximum temperature encountered is 25°C (air has a greater capacity to hold moisture as temperature increases). If the temperature went as high as 35°C and the relative humidity were 100%, the speed of sound would be increased to about .8% over that of dry air.

Whether humidity has to be compensated for depends on the temperatures and relative humidities encountered in a particular mine and the measurement accuracy level desired. It is quite simple to incorporate a solid-state

temperature sensor into a measurement device but it is not as easy to measure humidity. There are three possible options for humidity compensation. The first option is to put in a fixed compensation for a mean value of humidity and not provide any correction for deviation from the mean. The next option is to provide the unit with a relative humidity reading, entered automatically from an internal sensor or manually if an external device is used. The last option is to calibrate the unit by measuring a hole of a known length.

3.2 CIRCUIT DESCRIPTION

3.2.1 Measurement Circuit Block Diagram

The electronics used in measuring hole length can best be explained by referring to the block diagram (Figure 6). The first choice an operator would make is to select the appropriate mode of operation. There are two basic types of output that can be selected, either continuous or pulsed (burst). The unit has four modes: internal sine, external sine, amplitude modulated, and burst. The first three are continuous and the latter is pulsed. The pulsed mode is used for muck pile height measurement. The remaining three modes are used for blasthole measurement.

In order to measure the hole, either a pure sine wave or an amplitude modulated sine wave can be used. The pure sine wave can be generated by an internal oscillator (variable oscillator #1) located inside the device, or by an external oscillator. The external oscillator is connected via banana jacks on the front panel. The external oscillator was used almost exclusively during testing because it allowed the use of a laboratory grade commercial oscillator. The only disadvantage of using the external oscillator was that it was more cumbersome.

Amplitude modulation is a technique DAVIS proposed to use in order to transmit higher frequencies yet detect lower frequencies. As explained in Section 3.1.1, lower frequencies provide lower errors. The problem, however, is that very low frequencies are beyond the capabilities of the speaker, microphone, etc. An amplitude modulator essentially multiplies two signals which results in a translation of the signals in the frequency domain. A mathematical explanation is shown below.

If two sinusoidal signals are multiplied together an amplitude modulated signal is created. Suppose there is one signal called the carrier at a frequency f_c and one called the modulator at a frequency f_m where $f_m \ll f_c$.

$m(t) = A_m \cos 2\pi f_m t$, the modulator
$c(t) = A_c \cos 2\pi f_c t$, the carrier

Using the trigonometric identity

$$2 (\cos A) (\cos B) = \cos (A+B) + \cos (A-B)$$

Then,

$$m(t) \cdot c(t) = \frac{A_m A_c}{2} \cos 2\pi(f_m+f_c) + \frac{A_m A_c}{2} \cos 2\pi(f_m-f_c)$$

This results in two pure tones at frequencies $(f_c - f_m)$ and $(f_c + f_m)$ which results in a beat frequency of $2f_m$.

The advantage of this approach is that f_m may be one of the lower harmonics of the hole and the receiver could detect this. However, the frequencies transmitted would be up around f_c which could be selected to be in the linear region of the speaker and microphone.

The disadvantage of this system is that there is added circuit complexity. Also, erroneous resonance detection could occur if the lower sideband $(f_c - f_m)$ fell into the non-linear region of the system, or if the upper sideband $(f_c + f_m)$ was above the cutoff frequency of the hole. Although DAVIS did not completely rule out this technique, after a few experiments it was decided that it would be better to pursue the pure sine wave mode.

With regard to the block diagram, it can be seen that the modulator frequency, f_m, could be provided by either variable oscillator #1 or an external oscillator. A switch on the front panel selects the modulator. The carrier frequency is provided by variable oscillator #2. When the amplitude modulation mode is selected the mode select switch puts oscillator #2 into a continuous mode, via the TDR Burst Controller.

The last mode available is the pulsed mode. In the pulsed mode, the output would come from oscillator #2. The frequency of oscillator #2 is controlled by a knob on the front panel (as is the case for oscillator #1). Two more knobs allow control of the rate and duration of the burst. For example, suppose the operator wanted to send a single cycle burst of a 1 kHz sine wave once every second. He would set the frequency of oscillator #2 to 1 kHz, the rate to 1 Hz, and the pulse width to 1 ms.

Whichever mode is selected, the output of the mode selector goes through an adjustable gain power amplifier and out to the speaker via banana jacks.

The sound waves are then picked up by the receiver, a back electret microphone. The microphone is connected via a bnc connector and amplified by an adjustable gain pre-amp. The signal can be examined by an oscilloscope either normally or rectified. In some instances, rectifying the signal makes peak detection easier. Detailed schematics are provided in Appendix B.

Bore Hole Test Circuit

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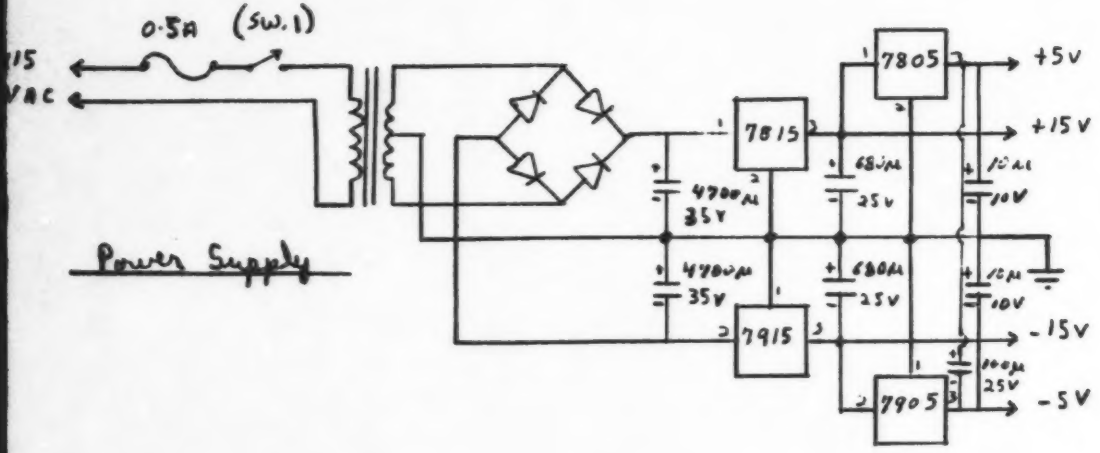
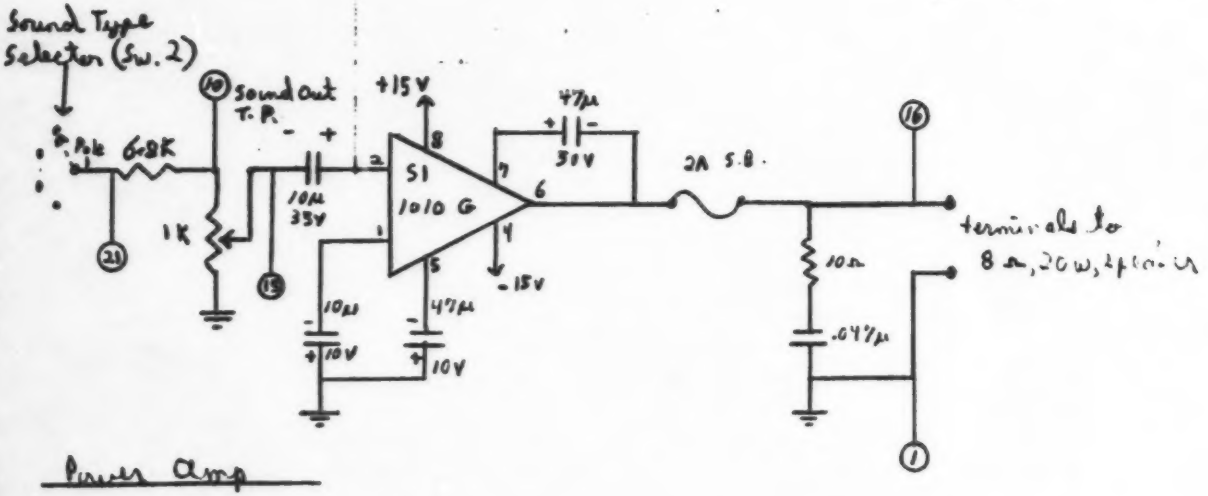
Note:

(N) denotes pin # of lid interconnect cable.





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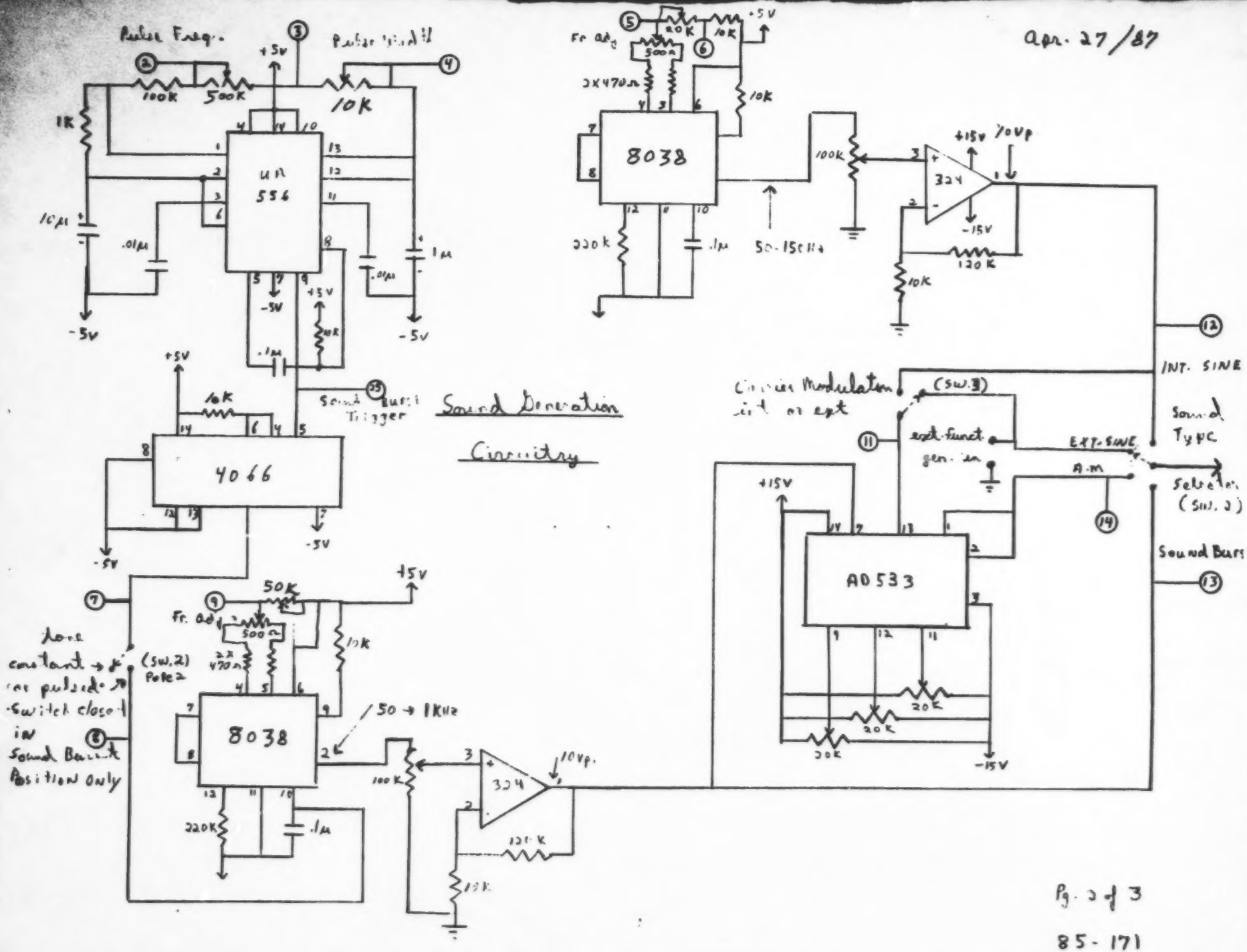
Sound Generation Circuitry



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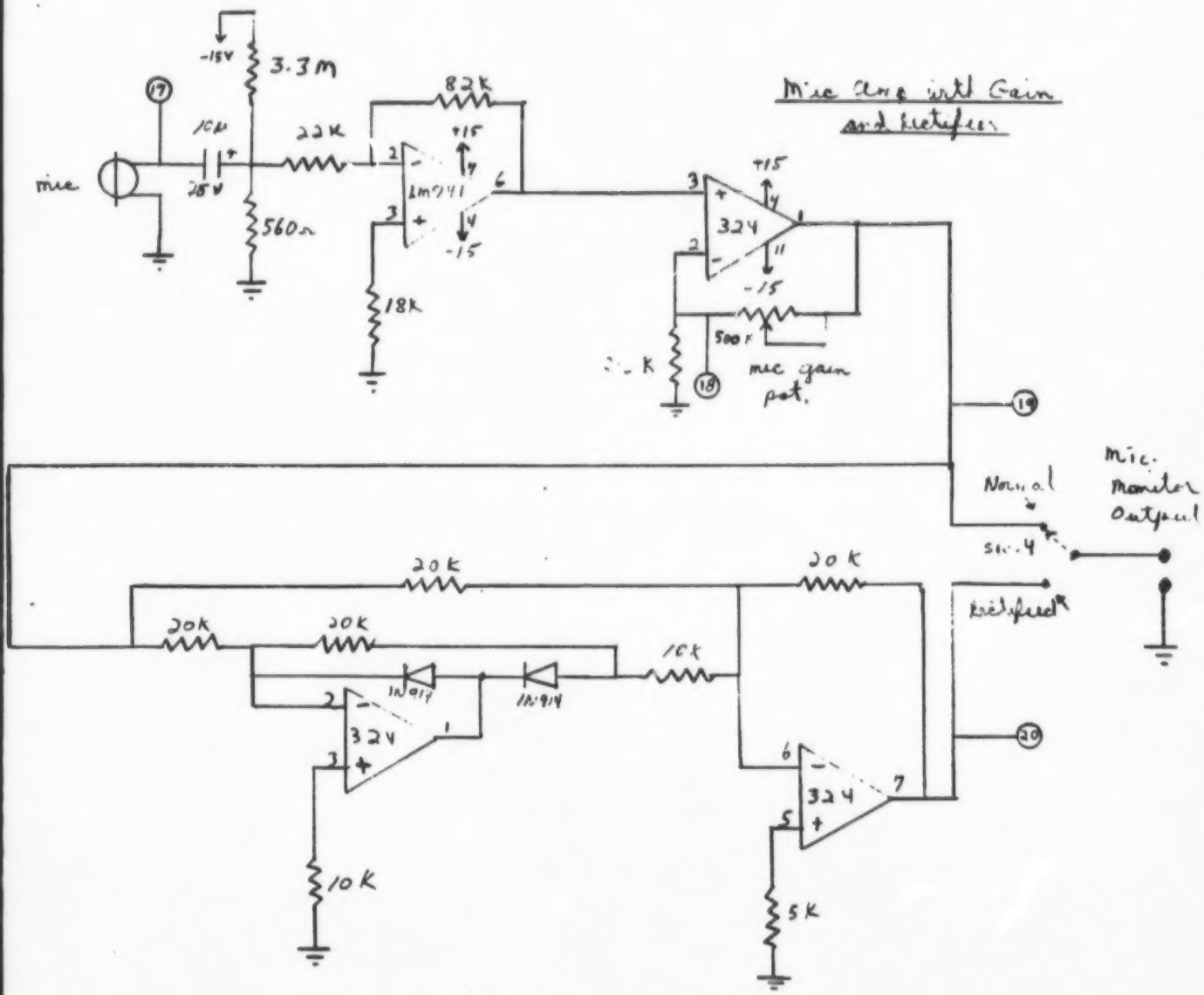

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MEASUREMENT CIRCUIT BLOCK DIAGRAM

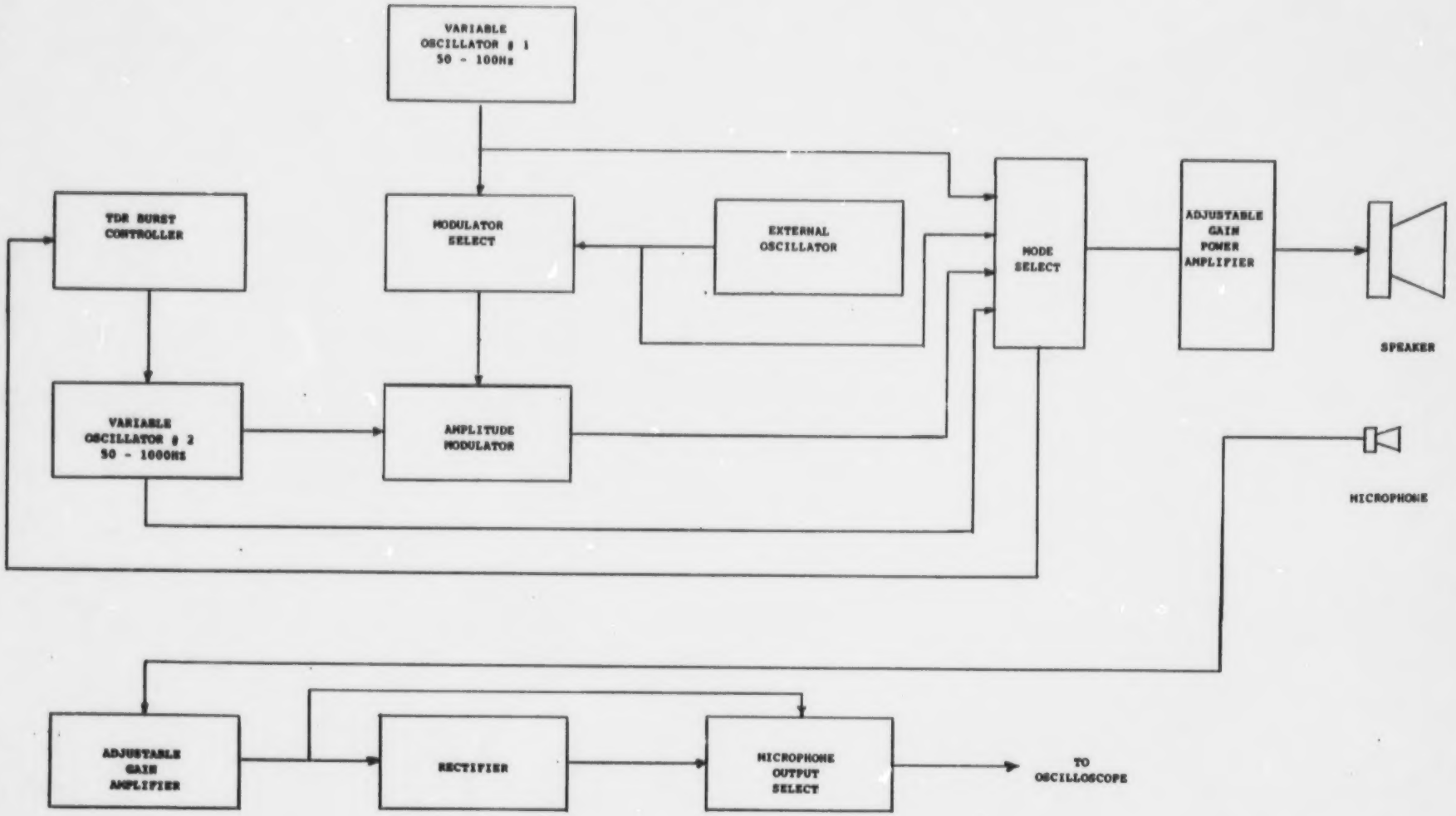

FIGURE 6 SYSTEM BLOCK DIAGRAM

4.0 MUCK PILE MEASUREMENT

4.1 INTRODUCTION

This section outlines the activities and results relating to the investigation of Time Domain Reflection (TDR) techniques as applied to the measurement of the distance between the top of a blasthole and the muck pile below. Since the Milestone "A" Report, DAVIS has spent considerable effort studying muck pile measurement.

4.2 PRINCIPLE OF OPERATION

The TDR technique involves the measurement of the time between the transmission of an acoustic pulse and the reception of the same pulse after it has reflected off a target surface. The time measurement relates to the distance between the signal source and target by the following function;

$$D = 1/2\ ct,$$

where D is the distance, c is the velocity of sound in the transfer medium and t is the measured time between transmission and reception of the return echo. The factor of 1/2 accounts for the fact that the pulse travels to the target and back which is twice the actual distance between the source and target.

Systems such as radar and sonar are based on TDR and the range of frequencies encountered can vary widely depending on the application.

4.3 PROBLEM UNDERSTANDING

The following subsections will discuss the requirements of the TDR instrument.

4.3.1 Range

The maximum anticipated operating range is 120 metres in the blasthole followed by 20 metres to the top of the muck pile. The minimum distances are 20 metres in the blasthole and 1 metre to the muck pile.

4.3.2 Resolution

The desired resolution of the distance to the muck pile is within .5 metres.

4.3.3 Transmitter and Receiver

It is preferred to use the same devices for the transmitter and receiver that will be used by the resonant measurement of blasthole depth. That is, a speaker for transmitting an acoustic pulse and a microphone to receive the return echo. Consideration must be given to matching operating characteristics of the transmitter/receiver combination, i.e. frequency range, efficiency, sensitivity, etc.

4.4 OPERATING FREQUENCY

One of the main issues in this design is the selection of an appropriate operating frequency to be used for the measurement. The effective range of the instrument is significantly affected by the selected frequency due to attenuation of the high frequency signals in air as compared to low frequency signals. Resolution of the distance is directly related to the frequency. The wave length of a 1 KHz signal in air is approximately .34 metres while a 10 KHz signal has a .034 metre wave length. These wave lengths represent the basic accuracy of the distance measurement at the respective frequencies.

4.5 SIGNAL ATTENUATION

There are several reasons for the return signal of a TDR system to be attenuated. Two were outlined in the Milestone "A" Report, namely absorption by the air and dispersion in muck pile. Reflection due to the impedance mismatch of the hole/muck pile interface was ignored for simplicity. It was noted that experimental results showed that this assumption was unacceptable. Since that report, DAVIS has reviewed the various attenuation factors and two important revisions were made.

First, a significant mathematical error was made in calculating the dispersion of the sound. Secondly, DAVIS conducted experiments to quantify the losses due to the impedance mismatch. Newly calculated theoretical losses

are shown in Section 4.6. It should still be noted that the calculations do not account for any reflections internal to the hole (from flaws, etc.) and they assume that the muck pile is normal to the incident wave and 100% reflective.

It would be useful at this point to define three terms used in acoustics:

Sound-power level: $PWL = L_w = 10 \log \frac{W}{W_{ref}}$ Re 10^{-12} W

Sound-intensity level: $L_I = 10 \log_{10} \frac{I}{I_{ref}}$ Re 10^{-12} W/m^2

Sound-pressure level: $SPL = L_p = 10 \log_{10} \left(\frac{P}{P_{ref}} \right)^2$

Re 2 X 10^{-5} N/m^2

In most instances, and for our purposes, $L_I \cong L_p$

The difference between these two values is usually just a fraction of a decibel.

Sound-power levels should not be confused with intensity levels or sound pressure levels, which are also expressed in decibels. Sound-power level is related logarithmically to the total acoustic power radiated by a source. Sound-pressure level depends on the "disturbance" produced at a point. Sound-pressure level depends on the distance from the source, losses in the medium, reflections, etc.

The absorption loss occurs over time and is an exponential function of the form,

$$\text{Loss} = A_{max}\, e^{-kd},$$

where A_{max} is the maximum amplitude of the pulse, k is an attenuation constant and d is distance travelled by the pulse. Attenuation constant k is strongly affected by the frequency of pulse and by the ambient temperature and relative humidity of air. Figure 7 shows the relationship between the attenuation constant, operating frequency, and the ambient temperature and relative humidity.

The transmission coefficient due to the impedance mismatch was measured experimentally. A microphone was placed in the centre of a 12 metre pipe and the speaker was placed

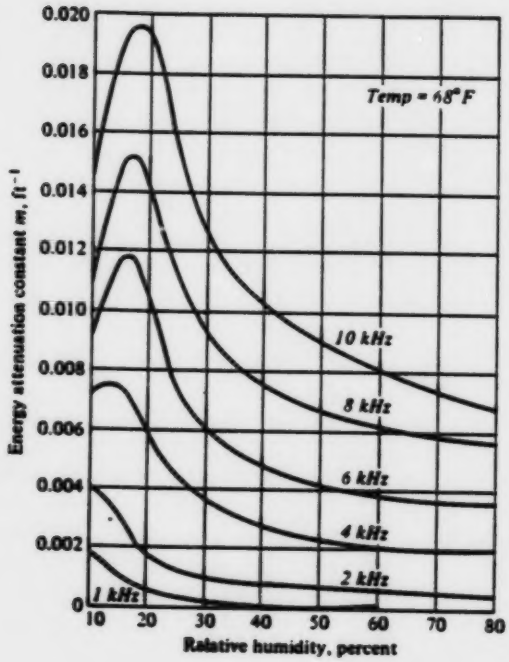

FIGURE 7 ATTENUATION CONSTANT FOR SOUND WAVE IN AIR

at one end. A pulse of one cycle was sent out for various frequencies and the outgoing signal was compared to the return signal. The microphone was placed at the center because when it was placed near the speaker there was a large pressure increase in the return signal as it struck the closed end. For frequencies below cutoff 35% of the signal was transmitted and 65% reflected.

Attenuation was assumed to be negligible. At frequencies above cutoff, attenuation increased significantly and microphone placement became critical. For these reasons, it was decided that only frequencies below cutoff would offer a practical solution.

4.6 CALCULATION OF LOSSES

The calculations given are for a 1 kHz signal.

L = blasthole length (metres)
d = blasthole diameter (metres)
c = speed of sound (metres per second)
h = muck pile gap (metres)
D = L + h

1st Case:

L = 120m h = 5m d = .15m

ABSORPTION LOSSES = -1.35 dB

IMPEDANCE MISMATCH LOSSES = 2 x [20 log .35]
(35% transmitted)

= -18.2 dB

$$\text{DISPERSION LOSSES} = 10 \log \left[\pi \left(\frac{d}{2}\right)^2 \cdot \frac{1}{2\pi(2h)^2} \right]$$

$$= 10 \log \frac{d^2}{32h^2}$$

= -45.5 dB

TOTAL LOSSES = -1.35 - 18.2 - 45.5 dB
= -65 dB

It is apparent that for the distances under consideration, and for frequencies below cut-off, absorption losses are negligible.

4.7 POWER REQUIREMENTS FOR TDR

If the muck pile were 20m instead of 5m, the total losses would be a -77 dB.

Since the sound return will be extremely weak, a very sensitive microphone is required. The microphone used by DAVIS had a sensitivity of -76dB (re 1V/µBar). Sensitivity in mV/µBar can be obtained as follows:

$$20 \log \frac{x}{1V/\mu Bar} = -76dB \quad \text{Re } 1V/\mu Bar$$

$$x = .158mV/\mu Bar$$

This is not a very sensitive microphone. To measure the extremely weak return signal, a sensitive instrumentation microphone is required. An example of such a microphone is a Brüel & Kjaer model 4145.

This microphone has a sensitivity of 5mV/µBar. When used with a Brüel & Kjaer model 2639 pre-amp this microphone can provide an output for SPLs ranging from 0dB to 145dB. This is enough dynamic range for a 20m muck pile (the 77dB drop in the return signal means under ideal conditions 77dB dynamic range would be required). This does not account for other losses such as reflection losses which would be in the order of 20dB.

In order to obtain a 0dB return pulse, a transmitted pulse of 97dB would be required (given a 20m stope). Assuming that the background noise is 60dBm an additional 20dB of power would be required to obtain a signal to noise ratio of -40dB. Typical loudspeakers have a sensitivity of approximately 92dB at 1m for 1W. For every 3dB increase in sound output, there is a doubling of power. This gives the following power requirements:

$$97+20dB - 92dB = 25dB$$

$\therefore$ 25dB above the output given by 1W is required.

$$\frac{25dB}{3dB} = 8.33$$

$\therefore$ there are 8 3dB increases. Each 3dB represents a doubling of power.

$$2^{8.33} \times 1 \text{ Watt} = 322 \text{ Watts}$$

Therefore, in order to measure a 20m muck pile, a prohibitive 322W of power would be required.

In order to measure a 5m muck pile, a dynamic range of only 65dB is required. This would be within the capability of the components described above. The amount of power required depends on what sort of return signal is desired. Naturally, the more power the better the return signal. An output in the tens of Watts (or perhaps hundreds) seems reasonable considering that this amount of power is only required for a fraction of a second. This may seem excessive, but it must be remembered that the 65dB figure does not account for a sloping muck pile, absorption by the muck pile, or reflections within the blasthole.

The cost involved in trying to measure the muck pile (even just 5m) is significant. A Brüel & Kjaer model 4145 microphone costs approximately $1400. The model 2639 pre-amp is another $1100 and the power supply (model 2804) for the microphone and pre-amp is $2000. This battery-powered power supply provides the 200VDC required by the microphone, the 120VDC required by the pre-amp, and has an internal buffer for the output of the pre-amp. In addition to the $4500 in microphone and pre-amp circuits, there would be additional hardware requirements for the measurement unit.

4.8 TDR SIGNAL PROCESSING CIRCUITS

The following subsections outline the criteria used to design circuits for measuring the distance to the muck pile and describe the circuits built for the initial testing of the TDR technique.

Design Criteria

The design requirements for the TDR measurement are as follows:

- Wide operating frequency range over the audio frequency band;
- Sufficient gain to overcome the theoretical losses;

- Adjustable power level for the transmitter, to compensate for sensitivity of the receiver; and
- Band pass filtering to reduce the ambient noise outside the operating frequency of interest.

Initial evaluation of the TDR technique in the audio frequency range started after the construction of the first two sections of the signal processor. This consisted of a pre-amp and an adjustable gain amplifier, a resonant band pass filter and a transmitter trigger circuit.

4.9 TDR EXPERIMENTS

After the construction of the amplifier and resonant filter circuits preliminary tests were conducted to assess the feasibility of the TDR technique.

4.9.1 Short Pipe Test

Hardware Configuration

The short pipe test was conducted using a single 4 metre length of pipe supported .75 meters above the floor, with the speaker sealed to one end and the other open and approximately 4.5 meters away from a wall. The microphone was placed in the pipe, 6 cm. away from the speaker.

Test Procedure

To determine if an object could be detected outside of the pipe a highly reflective steel plate was placed 2 metres in front of the open end of the pipe. Following this, the transmitter power level and frequency were adjusted until a return echo from the plate was detected at the output of the resonant filter.

Test Results

Figure 7 is a photograph of the observed waveform at the output of the resonant filter. The frequency used for the pulse was 4 kHz. The large pulse to the left is the transmitted signal and the small blip near the centre is the return from the end of the pipe. About 2.3 graticule divisions to the right of this is the target's return. This is in agreement with calculated results:

$$t = (2.3 \text{ divisions}) \times \left(\frac{5\text{ms}}{\text{div.}}\right) = 11.5 \text{ ms}$$

$$D = 1/2\ ct \qquad \text{where } c = 343\ \frac{m}{s}$$

$$= 1/2\ (343)(11.5 \times 10^{-3})$$

$$= 1.97\text{m}$$

$$\simeq 2\text{m}$$

Between the end of the pipe echo and the target are some low amplitude returns that were caused by reflections from the floor.

Attempts to repeat the experiment at a 1 kHz frequency didn't work because of severe reflections from the end of the pipe.

4.9.2 Long Pipe Test

Hardware Configuration

The same hardware configuration as in the short pipe test was used for the long pipe test except for the extension of the pipe to 20 metres. Four additional sections were added to the original length of pipe. A full wave rectifier circuit was constructed with its input connected to the adjustable gain stage output.

Test Procedure

A similar procedure was used in the long pipe test as used in the short pipe test except that high power levels were used by the transmitter and the output was observed after the full wave rectifier. The frequency used was 1kHz.

Test Results

Over the frequency range and transmitter power available it was not possible to detect the presence of a target near the open end of the pipe.

Figure 9 is a picture showing the output of the variable gain stage of the signal processor after passing through a full wave rectifier circuit. This picture shows regular echoes occurring between the transmit pulse and the end of

pipe echo located to the right of center. These regular echoes are generated by the pipe joints and are large enough to totally obscure any weak echo that might return from outside the pipe. You will notice that there are additional 'joint' echoes after the end of pipe echo. These are caused by the reflection of the return echo off the speaker which causes a retransmission of the initial pulse.

The reflections from the joints and the end of the pipe are located in agreement with calculations. The pipe was 20.55m long and there are 6 graticule divisions in the photograph.

$$t = (6 \text{ div}) \times \frac{20\text{ms}}{\text{div}} = 120\text{ms}$$

$$D = 1/2\ ct \qquad \text{where } c = 343\ \frac{\text{m}}{\text{s}}$$

$$= 1/2\ (343)(120\times10^{-3})$$

$$\approx = 20.58\text{m}$$

It can been seen that there are four equally spaced joints between the ends of the pipe.

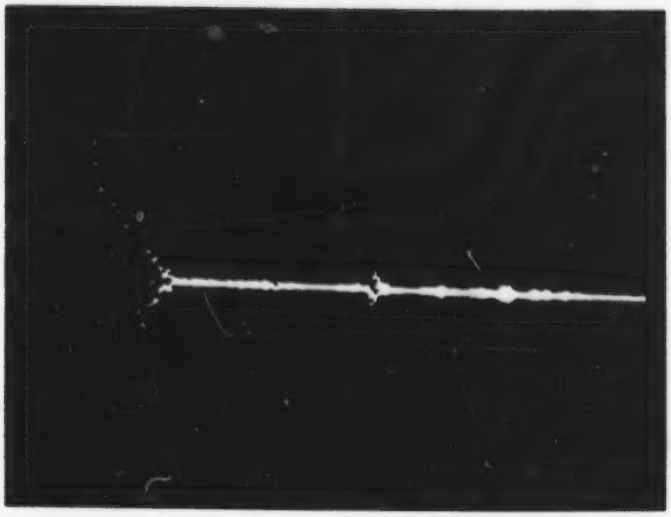

FIGURE 7 FILTER OUTPUT FROM SHORT PIPE TEST

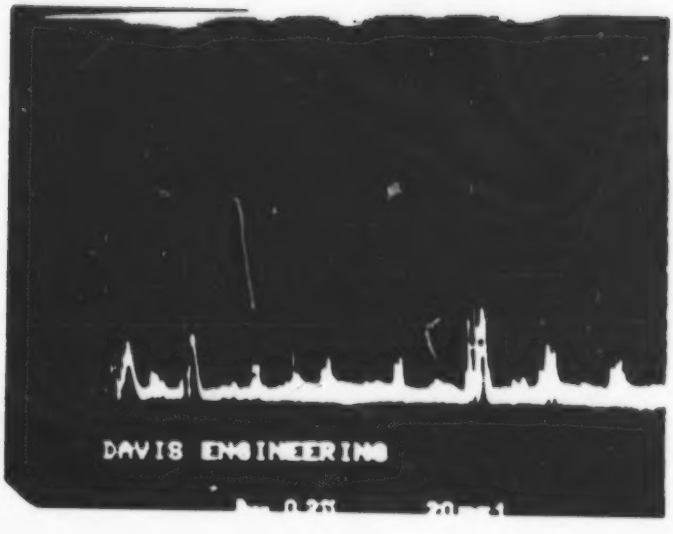

FIGURE 8 LONG PIPE TEST

5.0 FIELD TRIALS

The results of the Inco field trials are included in Appendix C.

Three holes were measured at Inco. The first two holes were closed and approximately 50' in length. These holes were consistently measured with errors less than 0.2%. The third hole was quite irregular and ended in a 9' void. The data points for this hole were extremely scattered, yet averaged out to have a reasonable 1.2% error. Averaging of five readings is not desirable in a commercial product because it would require additional complexity. The problems associated with the third blasthole may be due to the void at the bottom.

Even when using the traditional stick-and-rope method, several attempts had to be made to get the stick to rest properly. It is possible that the bottom of the hole was conical and the void was so small that the void was beginning to resonate.

TDR was attempted on all three holes as well. On the closed holes it provided reasonable results with a 3-5% error attributable to the accuracy of the oscilloscope cursors. On the open hole it was very difficult to resolve the bottom of the hole and there appeared to be a blur of multiple bounces in the "muck pile".

6.0 CONCLUSIONS

6.1 RESONANCE

From the tests conducted, it appears that blasthole measurement using resonance will work with consistency and the desired accuracy. Temperature, humidity and dust can be dealt with in a reasonably straightforward manner. Power requirements for resonance were modest, most measurements were made with less than 1 watt input power. The techniques of averaging -3dB points and of calculating n greatly improved the accuracy of the readings, without upgrading the components. Although not completely discarded, amplitude modulation is now believed to offer little advantage over an unmodulated signal.

6.2 TDR

Muck pile height measurement has had little success. Experiments indicate that the frequencies utilized should be below the cutoff frequency of the hole. Furthermore, attenuation due to absorption is nearly negligible when compared to losses due to dispersion in the stope and reflections at the hole/stope interface.

Frequencies higher than cutoff would improve the dispersion factor (higher frequencies spread less) but the increase in losses due to attenuation exceeds the gains due to directivity. Even with a relatively small stope, power requirements will be quite large. This would require a heavier speaker, battery, power supply and amplifier. The microphone would have to be quite sensitive and quite expensive.

7.0 RECOMMENDATIONS

It would seem that the costs and complexity of a device that provides muck pile height data are relatively high. At this point in time, the logical step would be to develop a commercial hole measurement device based on resonance and continue fundamental research on muck pile measurement.

Inco representatives indicated that a device that could only measure holes would still be of great value to Inco and several other Canadian mining operations. If the hole measurement device were commercialized and basic research on muck pile height continued, when the muck pile measurement problem was resolved, it could be incorporated into a second generation hole measurement device. The timing of such a development would probably fit in well with the goal of developing an automated mine.

As for the hole measurement device, it should be microprocessor based. This would allow the system to be automatic, sweeping and storing frequencies without the operator's input. The microprocessor would be well suited to making the required calculations and interfacing with a display and any input keys. By giving the device a bit of intelligence, it will be possible to make it easier to use by an unskilled operator.

Furthermore, a microprocessor system would be relatively easy to plug into a central data acquisition system.

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APPENDIX A
TEST DATA

RESONANCE EXPERIMENT DATA (PART ONE)

This portion of data was taken before Davis started to try averaging the -3dB points. Oscillator stability was approximately ±.1% and the error in detecting resonance is unknown. Due to the system components, there was distortion below approximately 90Hz. The technique for determining n±½ can only be used up to 129.5Hz, at which point the error is too great to determine n with certainty. It can be seen that the actual error occasionally exceeds the estimated maximum, particularly at low frequencies. This can be attributed to system non-linearities and the error in resonance detection. It can also be seen that in all but one instance the iterative technique reduced the error substantially.

RESONANCE MEASUREMENT DATA (PART ONE)

TEMPERATURE = 17.4°C L = 20.55m C = 341.76 $\frac{m}{s}$

CLOSELY COUPLED SPEAKER, END-OF-HOLE OPEN

RESONANT FREQUENCY (Hertz)	$L = \frac{c}{2\Delta f}$ (metres)	% ERROR ACTUAL	% ERROR ESTIMATED MAXIMUM	$L = \frac{c(n+\frac{1}{2})}{2f_0}$ (metres)	% ERROR ACTUAL	% ERROR ESTIMATED MAXIMUM
20.6						
28.5	21.63	5.3	± .6	20.86	1.5	± .1
36.7	20.84	1.4	± .8	20.97	2.0	± .1
44.8	21.10	2.7	±1.0	20.97	2.0	± .1
53.3	20.10	-2.2	±1.2	20.91	1.8	± .1
103.9						
112.5	19.87	-3.3	±2.5	20.53	- .1	± .1
120.9	20.34	-1.0	±2.8	20.50	- .2	± .1
129.5	19.87	-3.3	±2.9	20.47	- .4	± .1
138.0	20.10	-2.2	±3.2			
204.3						
213.0	19.64	-4.4	±4.8			
220.8	21.91	6.6	±5.6			
229.2	20.34	-1.0	±5.4			
303.8						
312.3	20.10	-2.2	±7.3			
320.3	21.36	3.9	±7.9			
403.2						
411.8	19.87	-3.3	±9.5			
420.7	19.20	-6.6	±9.6			
503.1						
511.2	21.10	2.7	12.5			
519.7	20.10	-2.2	12.1			

RESONANCE EXPERIMENT DATA (PART TWO)

This second portion of data for resonance utilizes the -3dB points to determine the resonance frequency. It can be seen that this reduced the error in every case except one. This is the same point that deviated in the previous data and probably reflects a disturbance such as self-resonance of the speaker. Once again, determining L using the iterative technique reduced the error substantially.

RESONANCE MEASUREMENT DATA (PART TWO)

TEMPERATURE = 20.6°C L = 20.55m C = 343.64 $\frac{m}{s}$

CLOSELY COUPLED SPEAKER, END-OF-HOLE OPEN

RESONANT FREQUENCY BASED ON PEAK AMPLITUDE (Hertz)	$L = \frac{c}{2\Delta f}$ (Metres)	% ERROR	RESONANT FREQUENCY BASED ON 3dB POINTS (Hertz)	$L = \frac{c}{2\Delta f}$ (Metres)	% ERROR	$L = \frac{c(n+\frac{1}{2})}{2\Delta f_n}$ (Metres)	% ERROR
21.38			21.17				
	23.13	12.6		21.00	2.2	20.39	-.8
28.81			29.35				
	21.03	2.3		21.37	4.0	20.58	.1
36.98			37.39				
	21.08	2.6		20.68	.6	20.68	.6
45.13			45.70				
	19.70	-4.1		19.86	-3.4	20.61	.3
53.85			54.35				
104.82			104.86				
	20.07	-2.3		20.55	0.0	20.48	-.3
113.38			113.22				
	20.78	1.1		20.68	.6	20.49	-.3
121.65			121.53				
	20.90	1.7		20.75	1.0	20.51	-.2
129.87			129.81				
	19.91	-3.1		19.93	-3.0	20.50	-.2
138.50			138.43				

APPENDIX B

CIRCUIT SCHEMATICS

APPENDIX C

INCO TRIALS DATA

DATA FROM FIELD TRIAL AT INCO

BOREHOLE #1

DIAMETER = 6.5"
ACTUAL LENGTH = 46.5'
END CONDITION = closed

RESONANT FREQUENCIES BASED ON AVERAGING OF -3dB POINTS (HERTZ)	Δf BASED ON ITERATIVE TECHNIQUES (HERTZ)	*L (feet) (BASED ON t = 11°C)
71.60		
83.30	11.92	46.51
95.40	11.91	46.55
107.25	11.92	46.51
119.35	11.93	46.47
131.45	11.94	46.43

* The temperature measured above ground was between 20°C and 24°C. Mike LeBlanc commented that the measuring tape and weight felt somewhat colder coming out of the hole than when they went in. The temperature of 11°C was derived by averaging the valves of Δf and calculating t based on the known length of the hole. This would be the same as a calibration run. If 20°C had been used, all the values of L would have gone up by about .7 feet.

BOREHOLE #2

DIAMETER = 6.5"
ACTUAL LENGTH = 47.5'
END CONDITION = closed, wet

RESONANT FREQUENCIES BASED ON AVERAGING -3 dB POINTS (HERTZ)	Δf BASED ON ITERATIVE TECHNIQUES (HERTZ)	*L (feet) (t = 14°C)
82.4	11.75	47.43
93.9	11.73	47.51
105.5	11.72	47.55
117.25	11.73	47.51
129.05		

* Once again temperature was calculated based on Δf and the known length of the hole. If 20°C were used, the lengths would be .47 feet longer.

BOREHOLE #3

DIAMETER = 10" liner for first 4', 7.88" for next 26.2'
ACTUAL LENGTH = 30.2'
END CONDITION = 9' void at end of hole, void bottom very muddy

RESONANT FREQUENCIES BASED ON OdB POINT (HERTZ)	Δf (HERTZ)	*L (feet) (t = 14°C)
65.8		
85.3	19.50	28.58
106.4	21.10	26.41
121.0	14.60	38.17
139.0	18.00	30.96
161.3	22.30	24.99

AVERAGE L = 29.82'

The irregularity of this hole seemed to produce quite a bit of scatter in the values of L. It's possible the void was small enought in diameter that it too was being resonated. It was impossible to average -3dB points because amplitude variations were under 2dB.

In all of Davis' tests so far, averaging several points seems to give good results, as is the case here.